SPATIAL EVOLUTION OF THE RIVER VALLEYS UNDER THE INFLUENCE OF ACTIVE VOLCANO: A CASE OF MERAPI VOLCANIC PLAIN

Arif Ashari [1], Suhadi Purwantara [1], Nursida Arif [1], Edi Widodo [2]

[1]Department of Geography Education, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia
[2]Geography Education Master Program, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia

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Abstract: Merapi Volcano in Central Java, Indonesia, has a high eruption intensity that triggers landscape changes in the form of a river channel evolution. In this paper, the spatial change of river valleys under the influence of sediments deposition in the fluvio-volcanic system is investigated. The data were collected by employing observation, remote sensing image interpretation, literature study and documentation of data from several agencies. The data were analysed using the spatial approach supported by geographic information system (GIS) and remote sensing. The results show that there are many palaeochannels related to fluvio-volcanic processes from the southern to the western sectors of the Merapi volcanic foot. Palaeochannels are mainly distributed next to the main river valleys. This condition correlates with the contributions of the Merapi eruptions. The palaeochannel distribution patterns cluster radially following the distribution pattern of the river valleys. The process that plays the most important role in the evolution of palaeochannels is the deposition of lahar. In sum, this research shows that volcanic activities over a long period of time have provided great and important contributions that have driven the landform evolution. The various changes that occur also reveal the unique morphological characteristics, showing the influence of the volcanic processes.

Keywords: landscape evolution, palaeochannel, volcanic landform, Merapi Volcano

Corresponding author: Arif Ashari; arif.ashari@uny.ac.id

Introduction

Java is one of the islands in the region of the Malay Archipelago (Indonesia and adjacent islands) which has complex landscape conditions and evolution history. The morphological complexity in Java has resulted from joint endogenous and exogenous processes. The endogenous processes include tectonism and volcanism that are associated with the collision of tectonic plates between Southeast Asia and Indo-Australia (Verstappen 2010). Due to tectonic plate collisions, Java was formerly part of Sundaland, which began to form in the Cretaceous (Hall 2009). Then, many geological processes related to tectonism occurred during the Cenozoic (Tjia 2014), followed by volcanism which became the framework for the morphological development till the present time. This endogenous process then joins with an exogenous process, which is characterised by a wet tropical climate with high temperatures and rainfall. This climate condition

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has led to a strong weathering followed by a rapid denudation process (Verstappen 2013). One of the events that show the importance of precipitation in the denudation process is lahar and flashflood in Merapi Volcano, which correlates with the monthly rainfall (Lavigne et al. 2000). Also, the sediment transfer process is not always constant because it is very dependent on the monsoonal rain variation (Lavigne and Thouret 2002). This condition shows that volcanism plays an important role in the landscape evolution in Java.

Java Island, which is located in the plate subduction zone, causes many volcanic events. In this regard, Verstappen (2013) explains that 47% of the volcanic eruptions in Indonesia occur in Java. In the central part of Java is Merapi Volcano, one of the most active volcanoes in the world based on the time span of its explosive eruption (Lavigne et al. 2000); it is even considered to be the most active volcano during the Holocene (Sudradjat et al. 2011). The explosive activities of this volcano have been occurring for approximately 10,000 years (Newhall et al. 2000) and happening continuously with an average eruption span of 1–7 years (Andreastuti et al. 2006). The intensive activities of Merapi Volcano have affected the evolution of the landscape, for example, the disappearance of palaeolakes in Borobudur, which has been occurring gradually since the Pleistocene (Gomez et al. 2010, Murwanto et al. 2004, Newhall et al. 2000).

In the Merapi volcanic foot, especially from the western to the southern parts, there are many palaeochannels which show the existence of ancient river valleys. A palaeochannel is a geomorphological expression of abandoned river channels (Chen et al. 1996a, b). These palaeochannels are widely distributed and tend to be situated next to the present river valleys. This condition may relate to the shift of the location of a river valley. The river flow changes are affected by the eruption materials transported through the river (Maruyama 1993), namely lahar materials which block the river valleys, causing the river to form new river channels (Murwanto et al. 2013). The blocking channel mechanism occurs as a result of lahar deposition in a part of the old channel. The western to southern parts of Merapi Volcano include the areas which are mostly affected by eruptions from the past (Andreastuti et al. 2006). In this region, a lot of lahar deposition processes which have been identified from 1822 to 2010 are found (Lavigne et al. 2000, Murwanto et al. 2013). Continuous lahar deposition allows volcanic eruptions to control the shifting of the river valleys. It is interesting to know that the influence of volcanism in this region is so great from the past times that it plays a role in influencing the development of river valleys carried out by exogenous processes.

Today, palaeochannels are widely used as agricultural land, generally rice fields. The volcanic foot formed as a part of Merapi Volcano is formed from the volcanic eruption. Verstappen (2013) explains that the lower morphology of the stratovolcano is formed by lahar deposition. The process of deposition of lahar that forms the volcanic foot progresses gradually over a range of 50–150 years almost 20,000 years ago (Mulyaningsih et al. 2006). In addition to the deposition of lahar, the geomorphological development of the volcanic foot is also affected by huge eruptions which caused the collapse of the Old Merapi dome in the southwestern and western flanks (Newhall et al. 2000). Pyroclastic and lahar material deposition that occurred between 1500 and 2010 has been identified in 13 rivers located from the western to southern areas of Merapi Volcano (Lavigne et al. 2000, Lavigne and Thouret 2002, Murwanto et al. 2013). In relation to the existence of palaeochannels, it is predicted that a valley was formed by strong climatic influences during the rest period of the eruption; while in the eruption period, a large amount of material deposition blocked and changed the development of the valley. This may occur repeatedly. Palaeochannels have become a widespread problem, including in various landscapes affected by volcanism in various parts of the world. Early studies on palaeochannels related to volcanic activities have been carried out. Authors such as Wakabayashi (2013), Palmer (1991) and Schumacher and Schmincke (1990) have pointed out that deposition of volcanic materials and the process of aggradation play an important role.

In this paper, we describe the spatial change in the river valleys in the Merapi volcanic foot. The objectives of this paper are to analyse as follows: (1) the palaeochannel at the volcanic foot of Merapi Volcano, (2) the distribution pattern and the zonation of the palaeochannel and (3) the effects of volcanism on the dynamics of palaeochannel development. This research intends to explain that in the active volcanic landscape, eruption affects the development of river valleys, which are generally affected by the fluvial processes. The effects of eruption include the type of eruption and the eruption materials. This paper attempts to provide alternative information regarding the effects of past eruptions in the Merapi volcanic foot on the occurrence of river flows. This information can be used to support in disaster management and regional development that has been carried out.

Materials and methods

Data collection and analysis

This research employed a geographical approach and utilised geographical themes to analyse the problems. The data collected in this research consist of primary and secondary data. The primary data gathered from field observations include (1) palaeochannel locations, (2) morphography and morphometry of the landform, (3) geomorphological processes, (4) rock types and (5) land use. The data were collected by employing techniques such as observations, interpretations of remote sensing imagery, literature studies and documentations (Table 1). During the observation, we measured the location of the palaeochannel and the actual river valley using Global Positioning System (GPS.) Also, we measured the slope using abney level and geological compass. Moreover, we observed the morphography, geomorphological processes, rock types and land use. Then, we documented it utilising a digital camera and recorded it on the observation guide. Meanwhile, the secondary data were obtained from previous studies, literature sources, and previously published statistical data and maps. This method was also carried out to obtain data on palaeochannel locations, morphometry of the landforms, rock types and land uses. The secondary data obtained from the literature study consisted of data on past eruptions and sediment deposition that occurred after the eruption. These data were obtained from previous publications, namely Newhall et al. (2000), Andreastuti et al. (2000) and Gertisser et al. (2012). The data gathered from the documents were topographic and land use, which were collected from the Indonesian topographical maps. In addition, other secondary data include the chronology of the eruption and the distribution of erupted materials.

Table 1. Types of data, data collection techniques and instruments/data sources.

No	Data	Collection method	Instrument/data sources
1	Palaeochannel location	Observation	GPS, geological compass, digital camera
		Documentation	Documentation of Indonesian Topographical Map *(Peta Rupabumi Indonesia* or RBI Map*)* published by National Coordinator for Survey and Mapping Agency of Indonesia (2000)
		Remote sensing image interpretation	Quickbird Imagery (2015)
2	Location of actual river valley	Observation	GPS, geological compass, digital camera
		Documentation	Documentation of Indonesian Topographical Map *(Peta Rupabumi Indonesia)*
		Remote sensing image interpretation	Quickbird Imagery (2015)
3	Morphography and morphometry of the landform at palaeochannel	Observation	Abney level, digital camera, observation guide
4	Geomorphological process	Observation	Digital camera, observation guide
5	Rock type	Literature study	Newhall et al. (2000), Andreastuti et al. (2000), Gertisser et al. (2012)
		Observation	Geological hammer, geological compass
6	Land use	Documentation	Documentation of Indonesian Topographical Map *(Peta Rupabumi Indonesia)*
		Observations	Digital camera, observation guide

The technique used for observation is a geomorphological survey which is combined with analytical–geomorphological and synthetic–geomorphological surveys (Verstappen 2014). The utilisation of this method is based on the explanation by Clarke (2009) that a palaeochannel is a channel of palaeorivers that can be formed in contemporary land surfaces or subsurfaces, marked by channel forms or palaeochannel deposits. The sample locations for measurements and observations were determined systematically, following the main river valley paths that are located on the Merapi volcanic foot. There are eight main river valleys in that area. Some rivers

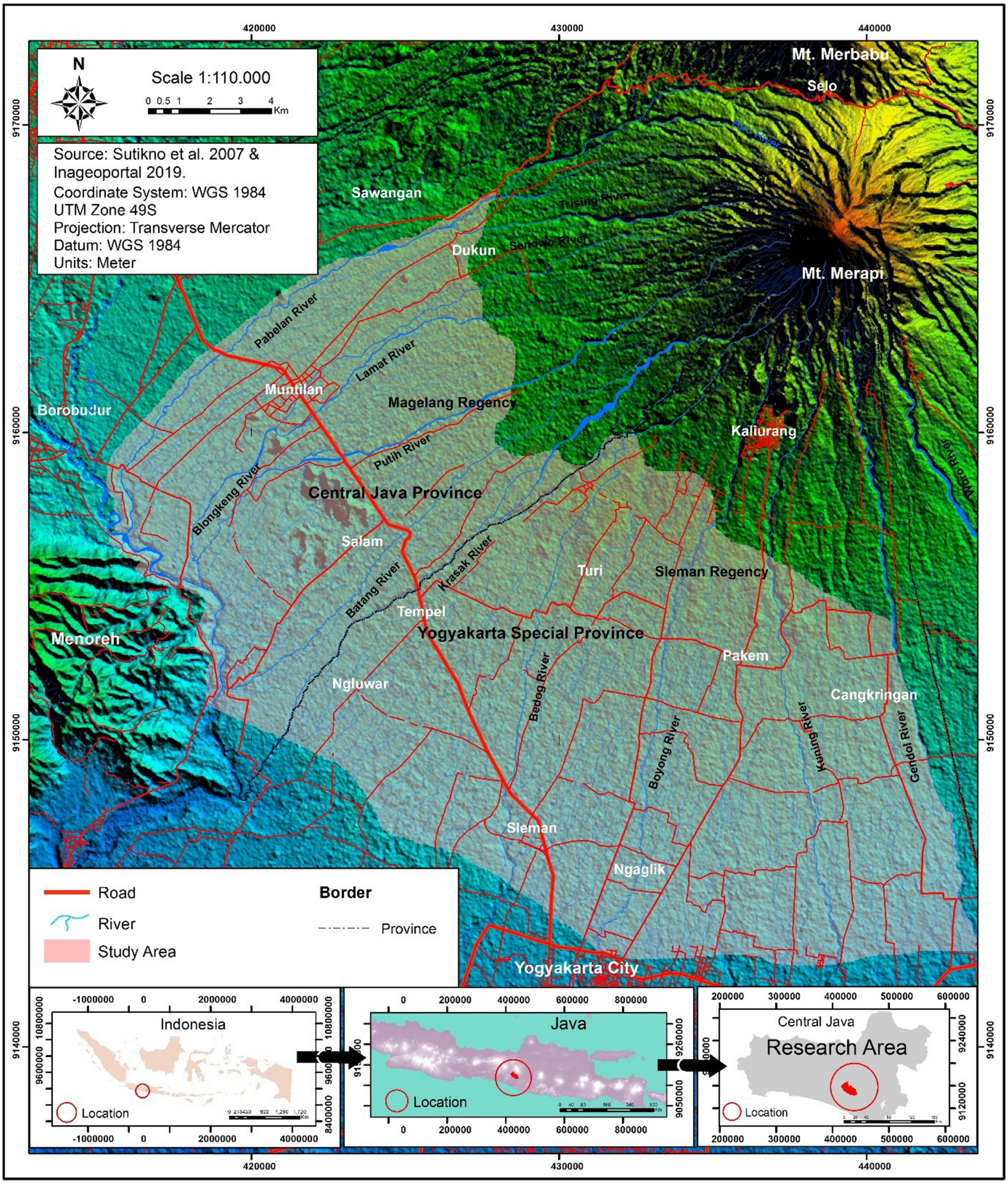


Fig. 1. Study area.

are joint rivers that flow the lahar from Merapi volcanoes, so that the total is 13 rivers, as explained by Lavigne et al. (2000). The eight rivers include (1) Pabelan (a joint of the Apu, Trising and Senowo Rivers), (2) Lamat, (3) Blongkeng, (4) Putih, (5) Batang, (6) Krasak (a joint of Krasak and Bebeng Rivers), (7) Boyong, (8) Kuning and (9) Gendol (Fig. 1).

The data analysis employed in this research is descriptive–spatial, supported by GIS analysis. The initial step in this analysis is identifying the presence of a palaeochannel in the research area. Palaeochannel identification is carried out by combining morphological observations and morphometric measurements. In this process, we combine terrestrial surveys, visual identification through Quickbird imagery and calculation of soil moisture index based on processing of Landsat 8 OLI imagery. The palaeochannel area was assumed to have higher average humidity than the surrounding land in calculation of the soil moisture index. The second step is performing a buffering analysis to determine the distance of the palaeochannel from the existing river valley. This step was strengthened by the average nearest neighbour (ANN) analysis in the third step. The ANN analysis is utilised to determine the palaeochannel distribution patterns. In this process, the *z*-score and *p*-value is used as an indicator of the type of distribution patterns (Nirwansyah et al. 2015). The formula in the ANN analysis, referring to Aziz et al. (2012), is as follows:

$$R = \frac{r_{obs}}{r_{exp}} \quad (1)$$

$$r_{obs} = \sum_{i=1}^{N} \frac{\min(d_{ij})}{N} \quad (2)$$

$$r_{exp} = \sqrt{\frac{A}{N}} \quad (3)$$

According to Aziz et al. (2012) in this formula, R is the ANN Index; r_{obs} is observed average

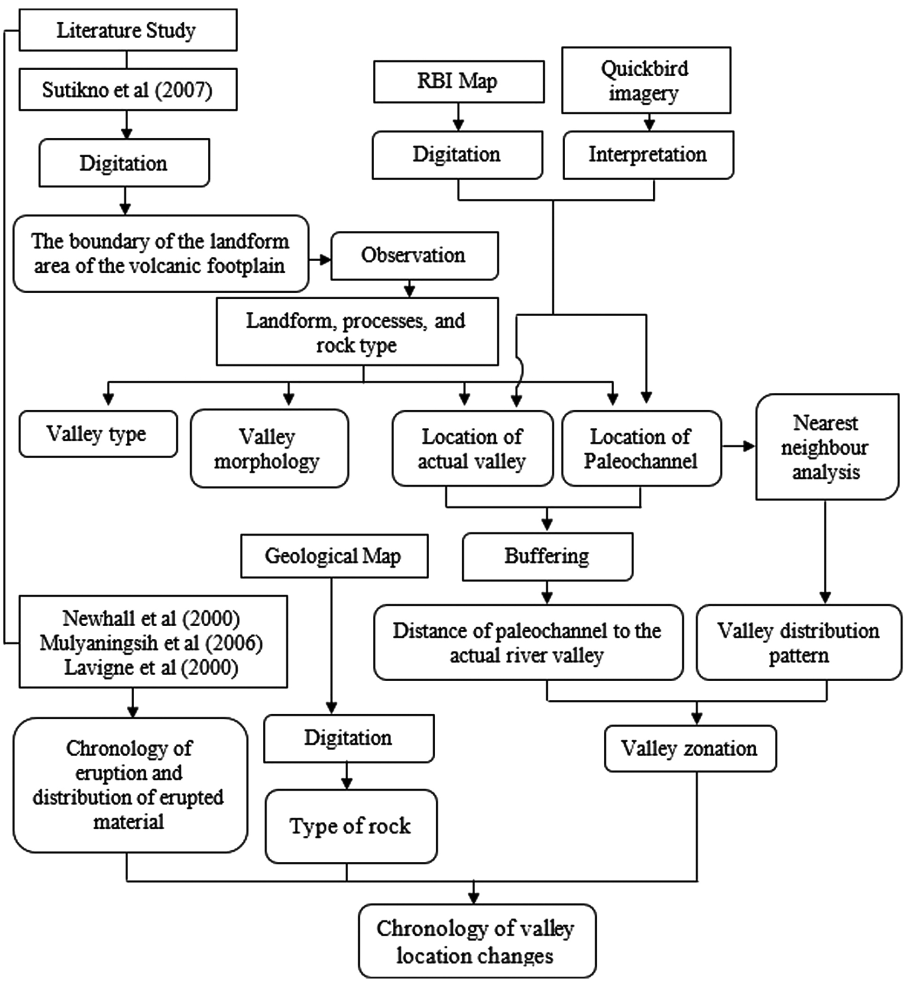


Fig. 2. Research procedure.

distance between nearest neighbor and r_{exp} is the expected average distance between the nearest neighbour determined by the theoretical pattern tested. min(d_{ij}) is the distance between each point and its nearest neighbour. A is the area and N is the number of points in the distribution. The purpose of calculating the value of R is to determine how clustered or dispersed locations of the case are within the particular area: If the R value is <1, the distribution pattern will be clustered; if the R value is totally equal to 1, the distribution pattern will be random and if the R value is >1, the distribution pattern will be dispersed.

Aurita and Purwantara (2017), Ratih et al. (2018) and Ashari and Widodo (2019) have utilised this method to analyse the spreading patterns of springs in the Merapi and Merbabu volcanic landscapes. There are three types of distribution patterns, namely clustered, dispersed and random. The clustered distribution pattern is shown by the negative z-score (−), the dispersed distribution pattern is indicated by the greater and positive z-score value (+), and the random distribution pattern is shown by the z-score value 0 or close to 0. The research procedures are p resented in Figure 2.

In this study, we also distinguish between palaeochannels at a distance of 500 m and those that are outside a distance of 500 m from the current river valley. The first group was identified based on the 500-m buffer area created from the current river channel. The purpose of creating a 500 m buffer is to explore further the findings of the previous studies carried out by Maruyama (1993) and Murwanto et al. (2013). Their research revealed that palaeochannels were found in the area of 100 m from the present river. Then, the authors trace up to 500 m and observe the trend on the existence of palaeochannels at a distance of 100, 300 and 500 m.

Study area

This research was conducted in the landform unit of the Merapi Volcano foot plain from south to west. The total area is 425.73 km^2. Physiographically, the study area lies at the lower side of the morphological cone of the Merapi Volcano, which is bordered by landform units of volcanic foot at the top and fluvio-volcanic plain at the bottom. Administratively, the research area is located in the middle of Java Island, namely in the Central Java Province and the Yogyakarta Special Province (see Fig. 1).

Based on the Geological Map of Yogyakarta (Raharjo et al. 1995), most of the research area is composed of materials from the eruption of the Merapi Volcano. Most of them resulted from the eruption of Young Merapi episodes. The old Merapi material is found in small amounts in the southwest of Gendol Hills. Newhall et al. (2000) explain that the Gendol Hills consist of several hills located along 20 km, stretching from the western to the south-western part of Merapi. These hills are 150 m high above the surrounding rice fields, which are composed of hornblende and pyroxene andesite, which have been weathered. Van Bemmelen argues that these hills were formed due to the collapse of the Old Merapi in 1006 AD. Meanwhile, Berthommier (1990) and Camus et al. (2000) reinterpret the Gendol Hills to be hummocks of the Mount St. Helens-like debris avalanche. Another interpretation of Newhall et al. (2000) is that these hills are erosional remnants of the pre-Merapi volcanic terrain. Meanwhile, the area around the hills, like the plain area of the volcanic foot in general, is composed of young lahar deposits such as lahar in 1969 deposited through the Senowo River, Lamat, Blongkeng, Putih, Bebeng, Batang, and Krasak; and larger lahars in 1931 that travelled down the same rivers (Newhall et al. 2000). In general, the materials from the Merapi eruption which compose the study area are pyroclastic flow and lahar deposits. The youngest material of pyroclastics and lahars are found in the south-west (Gertisser et al. 2012).

The research area has a moderate wet climate, indicating an average annual rainfall of 1,328 mm. Rain happens a lot in the wet months, which is 6–7 months a year. Relatively good rainfall affects the hydrological system, which is characterised by many rivers and much groundwater with a large discharge. The rivers that flow in the Merapi Volcano area are part of the Opak Watershed. Some other rivers are part of the Progo Watershed, which has a wider catchment area including other volcanic areas. In 2010, the average monthly discharge in Opak downstream reached 12.35 m^3 s^{-1} ranging from 1.89 m^3 s^{-1} to 83.2 m^3 s^{-1}. Past data show that the range of discharges during the heavy rainfall seasons (November–March) varies between 2.8 $m^3 s^{-1}$ in November and 50.7 $m^3 s^{-1}$ in March. In that period, the highest discharge was in April, reaching 60.7 $m^3 s^{-1}$. This condition is due to the characteristic of high infiltration in the Merapi Volcano area. The water level during the heavy rainfall seasons is 16.8–314 mm. These rivers are perennial even though the amount of flow decreases in the dry season. The groundwater potential is indicated by the presence of potential aquifers with discharge reaching 0.005–0.01 $m^3 s^{-1}$ (Sutikno et al. 2007).

Results

Palaeochannel at volcanic foot of Merapi Volcano

Many palaeochannels are found in this region and are thought to be connected to the evolution of the landscape in the past, which is controlled by the volcanic activities of Merapi Volcano. Chen et al. (1996a, b) explain that a palaeochannel is a geomorphological expression of abandoned river channels. The existence of a palaeochannel which connects with the eruption activities in the past has attracted the attention of previous authors. Maruyama (1993) states that Merapi Volcano had experienced seven major eruptions since 1900, namely in 1904, 1920, 1930, 1954, 1956, 1961 and 1969. The changes due to volcanic eruptions are mainly driven by the deposition of pyroclastic and lahar materials. The volcanic debris deforms the topography and changes the systems of drainage quickly. As a result, the position of the river valley has shifted repeatedly over a period of time and the old valley has become a palaeochannel. In his research, Maruyama identifies the shifts in several rivers located in the south-western flank of Merapi Volcano, including Pabelan, Blongkeng, Putih and Boyong Rivers.

Murwanto et al. (2013) conducted a research on the palaeochannel in the south-western flank of Merapi Volcano. In his research, palaeochannel identification was carried out by considering the morphological and sediment aspects. The palaeochannel is formed from the movement of rivers flowing upstream around the peak of Merapi and flowing lahar material, including the rivers of Senowo, Pabelan, Lamat, Batang and Putih. In the Pabelan River, evidence of the existence of ancient river valleys is shown by the remnants of lahar deposits in the form of andesite blocks found in dead river channels around today's river valleys. The land which was formerly used as a river channel is currently used for agriculture and fisheries. In the Lamat River, river channel shifts are identified based on the presence of widely spread lahar materials, and valleys that resemble river channels. Today, the former river channel land is used for ponds, agriculture, and settlements. In the Blongkeng River, the river channel changes occur due to the blocking of volcanic materials so that the river water flows to a different direction and forms a new channel. The precise time when the river shifted cannot be revealed yet, but the evidence of changes in the river channel can be clearly identified based on the material and morphology of the river terrace. Putih River is the most affected river by lahar in the past. The deposition of lahar also causes the displacement of river valleys, especially on the east side of the river. Batang River has also experienced a shift of its channel due to the blocking of the river channel by the lahar flow. The shifting river flow reaches upto 100 m in length from the river at this time.

Based on information from Maruyama (1993) and Murwanto et al. (2013), Ashari (2019) identified the distribution of palaeochannels in the volcanic foot of Merapi Volcano. The results indicate that the palaeochannel has specific characteristics both morphographically and morphometrically. Its size varies from being wide to narrow. There may be a relationship between the present river valleys and palaeochannels. The rivers that currently have wide valleys around them tend to have wide palaeochannels, and vice versa. In addition, the existence of a palaeochannel is not evenly distributed throughout the volcanic foot. The number of palaeochannels at the bottom of the volcanic foot is higher than at the top, which is likely influenced by the type of materials, the depth of the valley and the slope.

Based on the Quickbird satellite imagery (2015) and some of the images available on Google Earth (2019), 560 palaeochannels are identified in the study area. Referring to the classification of Chen et al. (1996a, b), the palaeochannel identified in the study area is a surface palaeochannel. The possible existence of a shallow-buried palaeochannel is not identified yet in this research. The surface of the palaeochannel spreads in various parts of the landforms at the volcanic foot in different sizes (Fig. 3). We further limit the focus of the study on the palaeochannel area around a large river valley, through which flows lahar material from the center of the Merapi eruption. This is in accordance with the research problems about how the evolution of the landscape is affected by volcanic activities. Referring to Lavigne et al. (2000), we then determined a buffer area with a distance of 500 m from the river valley in eight major rivers in the study area, namely (1) Pabelan, (2) Lamat, (3) Blongkeng, (4)

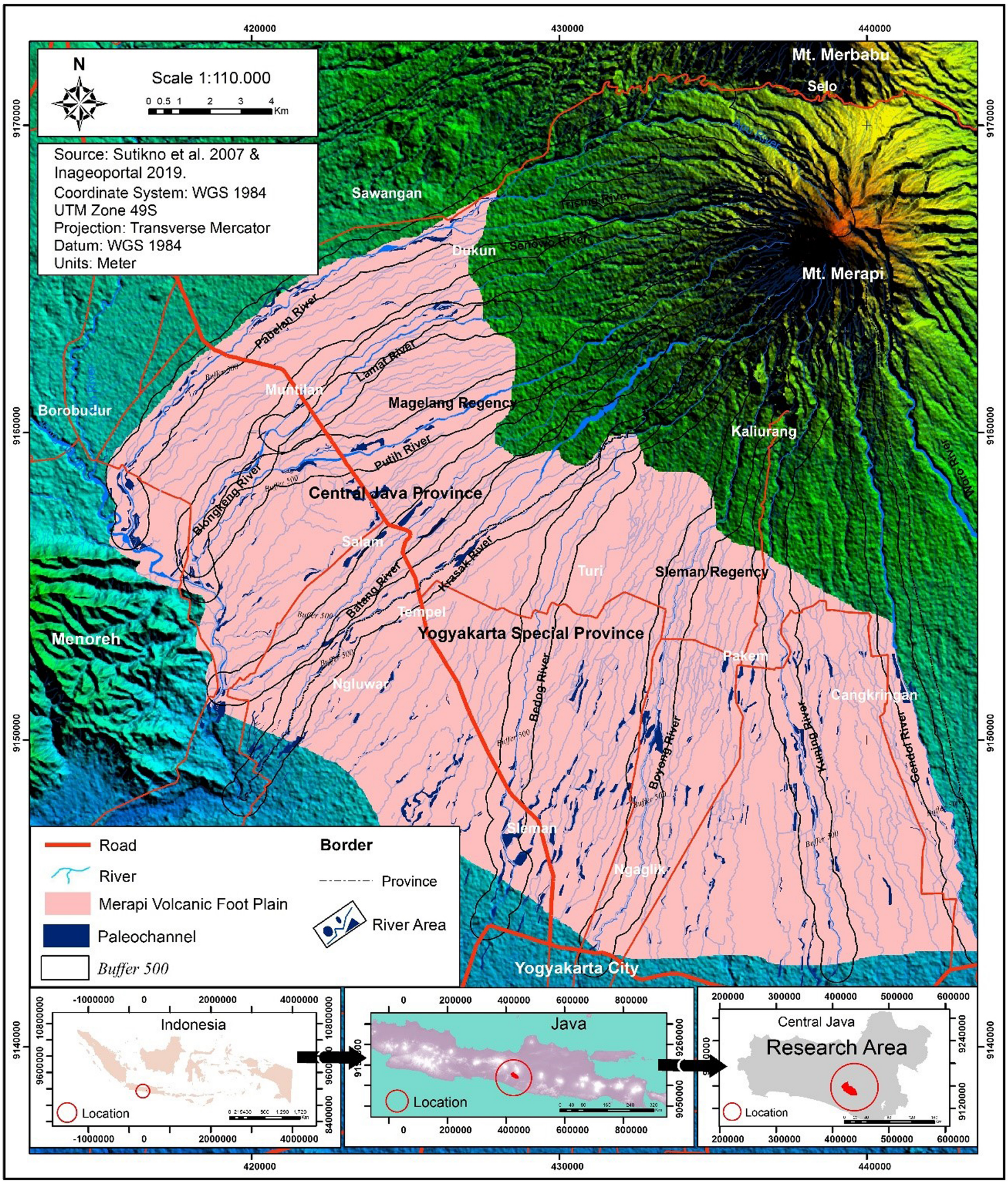


Fig. 3. Distribution of palaeochannel in study area.

Putih, (5) Batang, (6) Krasak (a joint of the Krasak and Bebeng river), (7) Boyong, (8) Kuning and (9) Gendol. The identification results in a 500 m buffer area of each of the river valleys, indicating that there are 251 palaeochannels.

The existence of 251 palaeochannels which are spread around the main river valleys shows that the rivers have experienced river channel shifts from time to time. Murwanto et al. (2013) describe that river channel shifts occur due to the deposition of lahar materials which block the river flows, so that the rivers form a new channel. The findings of their research indicate that a palaeochannel is mostly found in areas with a distance of 100 m (as identified by both of Maruyama (1993) and Murwanto et al. (2013)). In general, based on our findings, it is known that there are 53% palaeochannels at a distance of 100 m from the main river valley. The number decreases along with the increasing distance, 24% at a distance of 300 m and 23% at a distance of 500 m (Fig. 4). When identifying each river channel in detail, not all of the river valleys show the decreasing number of palaeochannels to the distance from the actual river channel. In the areas around Kuning, Krasak, Batang and Putih river, the number of palaeochannels found at a distance of 500 m is higher than that of 300 m. Even the number of palaeochannels is bigger than the distance of 100 m in the Krasak and Lamat areas. This condition indicates the possibility of river flow shifting to a relatively large distance in the past time due to the scale of the eruption and the amount of material produced. Actually, the identified palaeochannel may also be a continuation of other palaeochannels. The difficulties in identifying the palaeochannels are caused by the appearance of palaeochannels in the form of discontinuous fragments and various land uses.

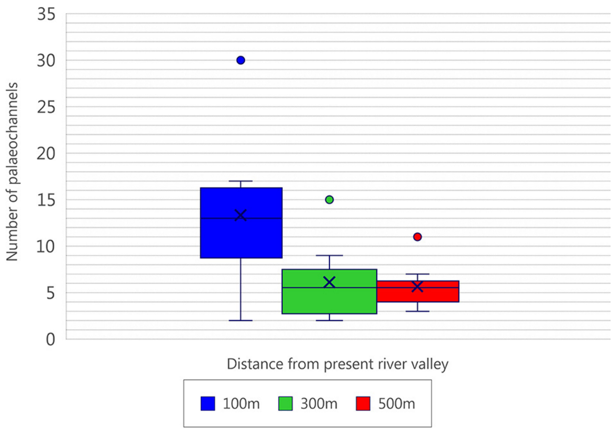


Fig. 4. The boxplot for the number of palaeochannels in the study area based on the distance from the present river valley.

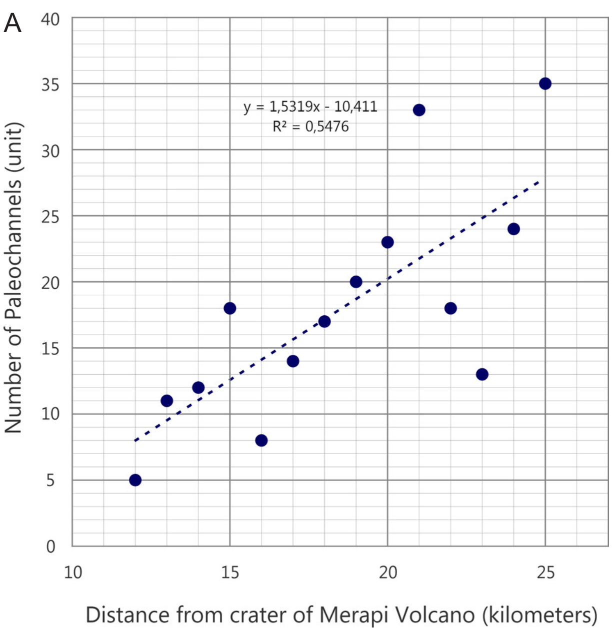
Based on the distance from the center of the eruption, palaeochannels generally spread at the bottom of the plain of the volcano foot. Ashari (2019) conducted an initial exploration of palaeochannels at the volcanic foot and found that river channel changes mainly occurred at the bottom of the volcanic foot, while at the top a few changes occurred. The possible factors that influence this condition are the types of material, the depth of the valley and the slope. In the transition region of the volcanic foot to the volcanic plain, pyroclastic and lahar deposits with deep valleys and steep slopes are found. The deep valleys may protect the river from the damage caused by the materials passing through it and the stockpiling valleys. The steep slope also speeds up the water flow through the valley, so it increases the force that moves the materials. The different morphological conditions are found at the bottom, namely the slope is gentler

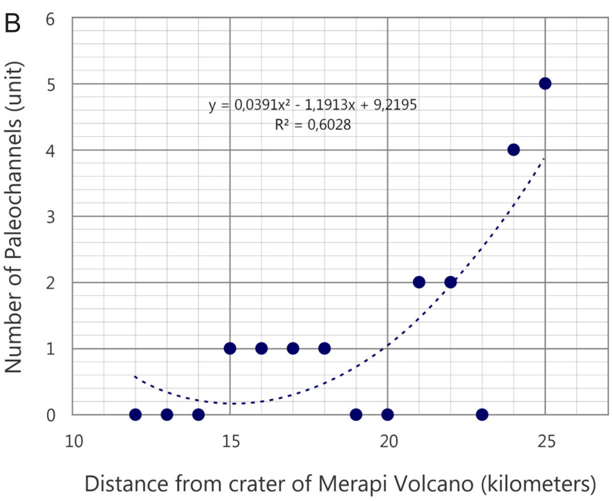
Table 2. The number of palaeochannels based on the distance from the eruption center.

No.	River	The distance from crater [km]														Total
		12	13	14	15	16	17	18	19	20	21	22	23	24	25	
1	Gendol	0	0	0	4	0	0	2	4	7	3	0	0	9	0	20
2	Kuning	0	0	5	5	1	3	5	2	1	1	0	1	1	0	25
3	Boyong	0	0	0	1	2	6	4	2	2	2	0	1	2	2	24
4	Bedog	0	0	0	0	0	0	0	2	3	6	3	4	3	2	23
5	Krasak	0	0	0	1	1	1	0	2	2	5	2	0	2	10	26
6	Batang	0	0	0	1	1	1	1	0	0	2	2	0	4	5	17
7	Putih	0	0	1	2	2	1	2	2	3	4	1	2	3	1	24
8	Lamat	0	5	2	1	0	0	0	0	2	2	0	0	0	0	12
9	Blongkeng	0	4	2	2	0	0	0	2	2	5	2	2	7	1	29
10	Pabelan	5	2	2	1	1	2	3	4	1	3	8	3	2	14	51
Total		5	11	12	18	8	14	17	20	23	33	18	13	14	35	251

while the valley is shallower with lahar material deposition. The more gentle slopes cause slower movements of the materials. This greatly fosters fluvial processes to shift the river basins. During the eruption, the river channel is blocked by the lahar materials, and then it is continued by the fluvial process in a calm period. The weak river flows cannot break through the lahar deposits, resulting in changes in the position of the river valleys.

Viewed from the distance to the center of the eruption, the study area is between 12 km and 25 km. The number of palaeochannels was identified in each kilometer from the eruption center (Table 2). The results show that 18% of palaeochannels was found at a downstream distance of ≤15 km from the eruption center, 33% palaeochannels at a distance of 16–20 km, and 49% palaeochannels at a distance of 21–25 km. When viewed in more detail in each kilometer, there is an increase in the number of palaeochannels at a greater distance from the center of the eruption. To further ensure the trend of the increasing number of palaeochannels to the increasing distance from the center of the eruption, a simple linear regression analysis was performed. The results indicate that there is a positive relationship between the increasing distance from the eruption center to the increasing number of palaeochannels with an R^2 value of 0.55 (Fig. 5). While a trend analysis conducted on each river shows a varied nature of relationship, some are linear and logarithmic, while polynomials dominate the nature of the relationship.





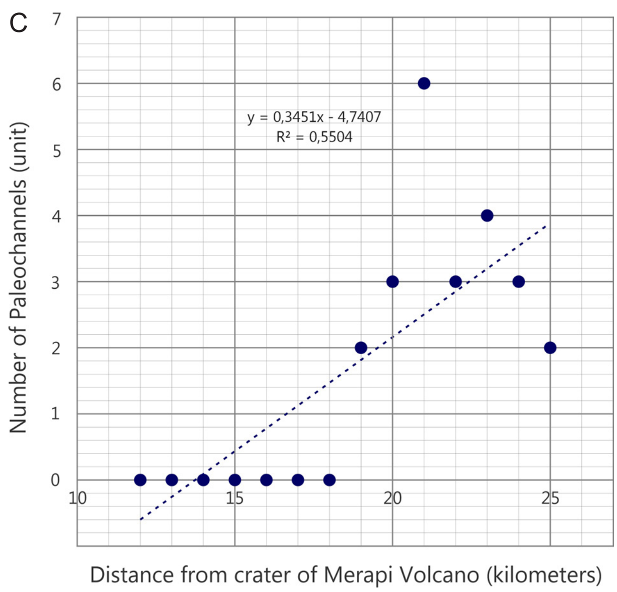


Fig. 5. The trend of the number of palaeochannels to the distance from the eruption center. (A) Entire area, (B) polynomial type from Batang River, (C) Linear type from Bedog River. Polynomial type indicates a change between increase and no increase in the number of palaeochannels, at each increase of downstream distance. Linear type shows that at each increase of downstream distance, there is an increase in the number of palaeochannels.

Based on the morphometry, the condition of the palaeochannels is relatively similar. Morphometric measurements performed at 60 palaeochannel sample locations (Table 3) show that palaeochannel depths in the study area generally range from 0.5 m to 4 m. In addition, three palaeochannels have a depth of >7 m. The average palaeochannel depth is 2.28 m. The width of the palaeochannels is 105.9 m. In general, there is no significant difference between palaeochannels in the western and southern parts. However, palaeochannels in the west tend to be shallower than those in the south. This was probably due to the large amount of lahar depositions in this area since 1961 (Lavigne et al. 2000). Furthermore, Lavigne et al. (2000) explain that the river valleys

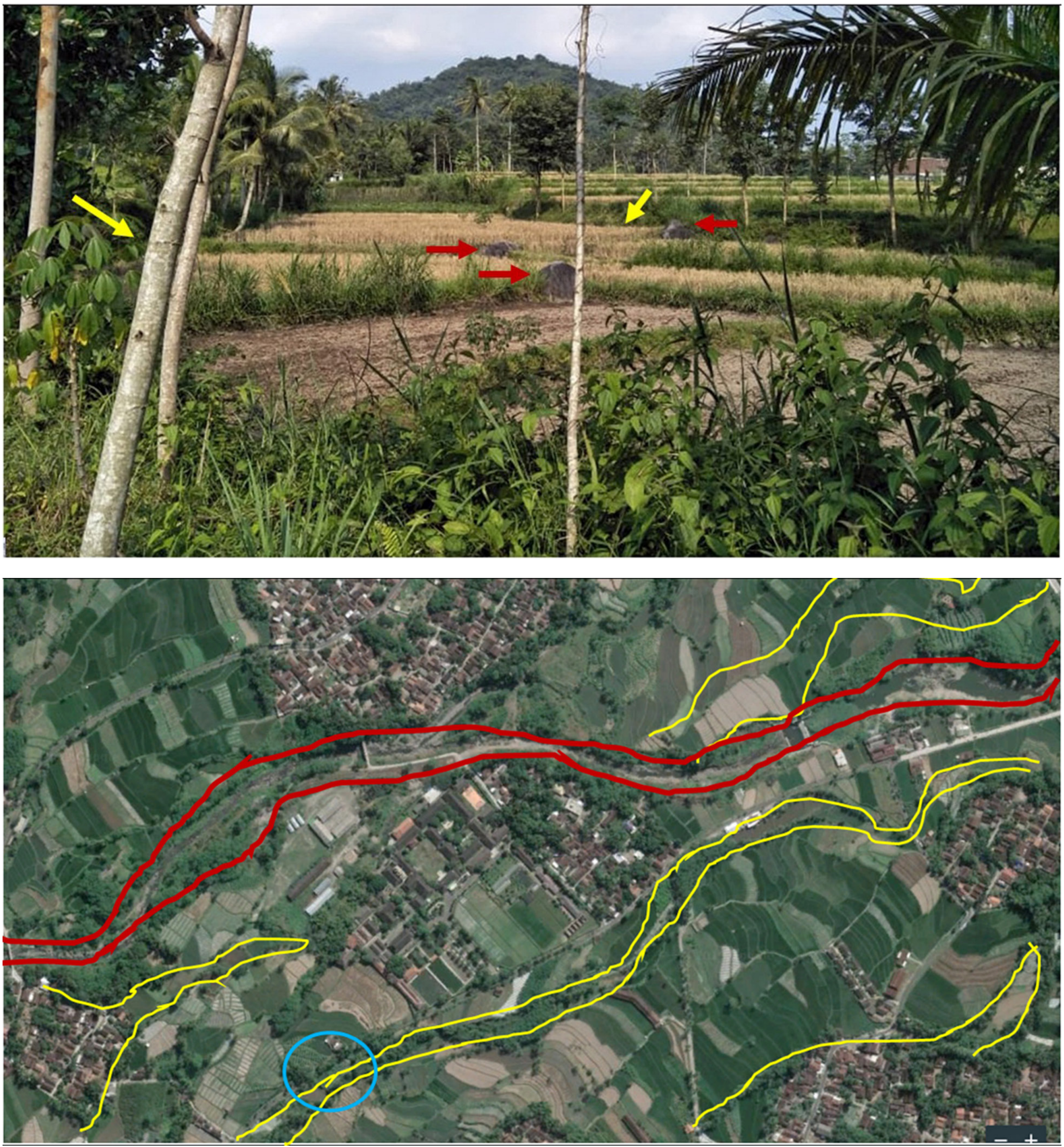


Fig. 6. The morphological characteristics of one of the palaeochannels in the Putih River. Above: The field situation (2019) shows a concave morphology (yellow arrow) with a depth of 1 m and base material of lahar deposits (red arrow). Below: plan view on Google Earth image (2019) shows several palaeochannels (yellow lines) around the current Putih River valleys (red lines).

Table 3. The morphometrical measurement of the palaeochannel in the research area.

River area	Depth [m]						Width [m]						Slope [%]					
	n	Mean	Median	SD	Max	Min	N	Mean	Median	SD	Max	Min	n	Mean	Median	SD	Max	Min
Gendol	4	1.25	1.0	0.5	2.0	1.0	4	88.00	67.0	64.02	180	38	4	5.00	5	0.00	5	5
Kuning	5	2.00	2.0	0.71	3.0	1.0	5	69.00	65.0	9.72	83	60	5	4.20	5	1.10	5	3
Boyong	7	1.14	1.0	0.38	2.0	1.0	7	67.43	60.0	25.01	112	44	7	9.86	10	4.26	18	5
Bedog	5	2.00	2.0	1.00	3.0	1.0	5	75.40	87.0	45.81	122	21	5	3.40	3	1.67	5	1
Krasak	11	2.00	2.0	1.20	4.0	0.5	11	169.27	162.0	53.89	277	91	11	3.73	3	1.01	5	3
Batang	7	1.14	1.0	0.63	2.0	0.5	7	96.57	82.0	57.57	179	11	7	2.71	3	0.76	3	1
Putih	8	1.19	1.0	1.16	4.0	0.5	8	66.88	54.5	39.24	155	33	8	3.25	3	0.71	5	3
Lamat	5	1.20	1.0	0.45	2.0	1.0	5	36.40	25.0	26.68	83	19	5	8.80	7	2.49	12	7
Blong keng	4	0.50	0.5	0.00	0.5	0.5	4	65.50	64.0	26.71	96	38	4	3.00	3	0.00	3	3
Pabelan	4	0.88	1.0	0.25	1.0	0.5	4	58.25	55.0	22.02	88	35	4	9.75	10	2.22	12	7

located on the western side range from 20 km to 30 km, except for the Pabelan River, which is 46 km. The channel slope is relatively large at 10–11%, except for the Batang River, whose slope reaches 14.7%. The thickness of lahar deposits varies between 0.5 m and 2 m, even though in the valleys it reaches up to 10 m. The valleys on the southern side have a gentler slope which is below 9%, but they are longer, reaching 30–40 km. The more gentle slopes allow intense lahar deposition, even though the number of lahar flows is not as much as on the western side. Palaeochannel conditions in the field are presented in Figure 6.

The distribution pattern and the zonation of palaeochannel

To show the extent to which volcanic activities influence the shifting river valleys in the volcanic foot, a palaeochannel distribution analysis was carried out using ANN analysis. The results of the analysis show that the distribution of palaeochannel is clustered as indicated by the p-value of 0.1 and z-score ≤2.58. This distribution has been identified qualitatively, as presented in Figure 3. There are two palaeochannel groups in general, namely (1) palaeochannels that existed within 500 m from the buffer area of the current river valleys and (2) palaeochannels beyond the 500 m buffer area of the current river channel.

Palaeochannel grouping around the main river valley clearly shows the contribution of volcanism in the development of palaeochannels in the study area. The volcanism process in the form of lahar material depositions which cause changes in the location of a river channel produces a palaeochannel. The process influences the formation of radial palaeochannel grouping patterns, which are spread linearly following the major river valley paths in the study area. This distribution pattern is a typical type of volcanic foot shape and volcanic foot plain. The radial distribution pattern which is linear with the river channel is influenced by the volcanic process and the morphology of the volcanic Merapi as a stratovolcano.

The second group of palaeochannels in the study area is located beyond the buffer area of 500 m from the current main river valleys. This palaeochannel group is mostly found in the southern part of Merapi volcanic foot. The palaeochannel is generally situated next to a small river valley or even not close to a river valley at all. This condition shows several possibilities: (1) the process which formed the palaeochannel is the same as that in the large river basin area, but it existed in the past so that the big river which experienced the flow changes does not exist anymore at this time; (2) it is formed by a fluvial process which removes volcanic materials by rivers that do not have an upstream at the crater of Merapi but at the lahar deposition area in the Merapi volcanic foot. This condition is indicated by the type of lahar materials found around the palaeochannel; (3) the volcanic events occur dramatically and affect the landform changes significantly. These possibilities still need to be studied and proven through further research. Specifically, the palaeochannel groups beyond the 500 m buffer area of the main river valley are not the main focus of this research.

With regard to the third possibility above, Bronto et al. (2014) explain that Merapi Volcano had experienced gigantic landslides to the south in the past. The avalanche reaches a distance of 30–35 km from the volcano with a volume of 10 km^3 and the areas affected are 300 km^2. This avalanche occurred before the Young Merapi period, therefore it might influence the development of past river basins. Furthermore, Bronto et al. (2014) also say that the avalanche sediment at a distance of 30–35 km was further refurbished until it became a lahar flow and reached a longer distance. The collapse of Old Merapi to the south and west was also confirmed by Newhall et al. (2000). The avalanche materials and its overhaul by this exogenous process also foster the development of river basin morphology in the past. At present, many river basin morphologies still exist but they are not connected with the main river valleys that originate from the center of the eruption of Merapi as a source of volcanic materials.

The southern to western flanks of the Merapi Volcano have undergone various physical changes during several stages of development. This allows the formation of complex morphological conditions at this time where the formation and development have been going on since the past time. The information showing the chronology of the evolution has been conveyed by previous researchers and will be discussed in the following section of this paper.

The dynamics of palaeochannel development and the effects of volcanism

The development of landforms that occur in the volcanic foot cannot be separated from the development of the Merapi Volcano landforms. Newhall et al. (2000) argue that the development of Merapi Volcano occurred in several stages, which include Proto Merapi, Old Merapi and New Merapi. Along with these stages of development, the evolution of landforms on the foot unit of the Merapi Volcano also occurs. Mulyaningsih et al. (2006) describe that Merapi Volcano, from the south to west sides, was a waterlogged environment during the initial stage of its development. From 20,000 years to 310 years ago, the development of landforms related to the activity of Merapi Volcano had occurred. During that period, Merapi Volcano deposited large volumes of materials and silenced the inundated areas till they became dry. Inundation to silting takes place gradually over a long period of time. This shows that Merapi volcanic activities greatly contributed to the development of landforms in the Merapi volcanic foot from the inundation areas to the plain areas. The precipitation of volcanic materials does not happen continuously, but there are alternating cycles within the 15–150 year period between eruptions that produce volcanic material, with a calm period that allows the exogenous process to erode the material and form river valleys.

Among the various types of volcanic materials, lahar deposition is an important factor which contributes to the development of river valley systems in the volcanic plateau. The explanation by Bronto et al. (2014) shows that lahar can also be formed by dismantling and re-transporting the pyroclastic materials and dome avalanches. This means that lahar flow not only occurs during eruptions. Because the lahar deposition process occurs continuously in a long span of time, this process may encourage the displacement of various river valleys that have been formed. The left river channel then develops into a palaeochannel, which becomes the valley of a dead river. The dynamics of lahar deposition determine the change in the landscape conditions. In some cases, this process is also supported by other processes such as the giant avalanche of the Merapi Volcano's cone.

The results of field observations also indicate that the basic materials of palaeochannel are lahar materials. In some places located near the transition zone, between the volcanic plain and the volcanic foot, pyroclastic deposits are also found. However, lahar material is mostly found in various palaeochannel sample locations in the study area. Lahar deposits increasingly dominate in areas which are far from the center of eruption. Lahar of Merapi can indeed reach a distance of 20 km from the center of eruption (Newhall et al. 2000). On the other hand, at a longer distance from the center of eruption, more palaeochannels are found. This further strengthens the prediction, as explained by Ashari (2019), that the deposition of lahar that takes place during the period of Merapi volcanic activities is a factor that influences the evolution of a palaeochannel.

When did the palaeochannel surface begin to develop in the volcanic foot? Observing the strong relationship between lahar deposition and the formation of the palaeochannel surface, the development of palaeochannels is not as old as Merapi Volcano. It should be noted that not all periods of Merapi Volcanic activities produce lahar materials. According to Newhall et al. (2000), during the Proto Merapi period, the Merapi volcano produced basaltic lava. Proto Merapi is the first development stage of the Merapi Vulkan, in which period the surrounding area was still an aquatic environment (Mulyaningsih et al. 2006).

Furthermore, in the Old Merapi period, lavas ranging from basaltic to andesite are produced, interspersed with pyroclastic deposits. An important event during the Old Merapi period that needs to be noted is the failure of Old Merapi, which produces avalanche debris on the south to west sides of Merapi. This event caused a river blockage (Newhall et al. 2000, Mulyaningsih et al. 2006) which produced a puddle; then it was followed by a very rapid accumulation of sediment around the base of Merapi Volcano (Newhall et al. 2000), so that the inundation areas turned into a plain. This process has been going on for at least 19,000 years BP. The results of deposition of debris material should form hummocks, but it was not found, so that Newhall et al. (2000) argue that the debris materials were buried by the accumulation of sediments that took place very quickly in the next period. Meanwhile, Bronto et al. (2014) found hummocks at the south approximately 30–35 km from Merapi Volcano. This condition shows that the deposition of Merapi volcanic material turned out to have a very large volume with a very wide coverage area. Newhall et al. (2000) describe that every year Merapi Volcano produces 106–107 m^3 of sediment. Every 1,000 years, there are 10^9–10^{10} sediments transported to the western and south-western slopes, and the accumulation of sediments that occur reaches 2–20 m in an area of 500 km^2. Due to the rapid deposition of volcanic material in large quantities, during the Old Merapi period, the landscape of the plain increasingly developed, piling up a previously formed pool environment (Mulyaningsih et al. 2006), and due to the influence of exogenous processes in the next period, the formation of river valleys occurred.

Observing the explanation above, researchers conclude that the sedimentation which occurs very quickly also triggers rapid changes in river valleys that have formed. The information from Gertisser et al. (2012) reinforces the possibility that palaeochannels had begun to develop in Old Merapi because most of the Merapi foot is composed of pyroclastic flow and lahar deposits from Old Merapi. In addition, Andreastuti et al. (2000) also found that Old Merapi deposits on the western slopes are in deep dissected valleys, different from other regions in general. Furthermore, because the same process continued even more intensely during the New Merapi period, the old main river valleys could be buried or shifted further to produce a palaeochannel that was relatively far from today's main river valleys. To ensure this, a study on the buried palaeochannel which we have not covered in this research should be conducted.

The New Merapi period was marked by explosive eruptions which produce ash and lapilli deposits as well as thick pyroclastic deposits that fill the river valleys (Newhall et al. 2000). Mulyaningsih et al. (2006) also explains that around the 11th–14th centuries Merapi's activities increased and resulted in larger volumes of deposits. Many inundation environments dried up due to the huge Merapi deposits in the form of lahar. During the colonial (16th–early 20th centuries) and post-colonial eruptions (late 20th century), Merapi experienced several large-scale eruptions, producing pyroclastic material in river valleys, lahar deposits around volcanic cones, and dome collapse on a smaller scale. Many temples from the past were buried in volcanic materials, especially thick lahar (Newhall et al. 2000).

The New Merapi Period, marked by explosive eruptive activities and producing a lot of lahar materials, is thought to be the peak period in the change in landscape conditions on the volcanic foot in the form of a river channel shift. This mainly occurred on the west–south-west side. Gertisser et al. (2012) explain that the western side contains many young pyroclastic flows and avalanche deposits, especially in major river valleys such as Pabelan, Blongkeng, Putih, Batang and Krasak. Meanwhile, in the southern side this is not found, except along the Boyong and Gendol Rivers. The old pyroclastic flow and lahar deposits are found in plenty. This condition caused palaeochannels on the western side to be located next to the present main valley. The process that occurs on the western side tends to occur in the final period. On the contrary, many palaeochannels on the southern side are located far from the present main river valley. This process perhaps occurred in the earlier period. In general, this area is composed of pyroclastic flow and lahar deposits, except in the western part which is interspersed with recent pyroclastic flow and lahar deposits. The lower part of the plain of the volcanic foot which contains many palaeochannels is composed of surficial deposits. This indicates that exogenous processes also contribute to the evolution of this palaeochannel instead of volcanism.

The most intensive sedimentation of lahar, which significantly contributed to the development of Merapi's volcanic foot, occurred during the New Merapi period. This is because lahar resources are in abundance from pyroclastic deposits on volcanic slopes. The pyroclastic materials deposited further from the center of the eruption were more potential in triggering the larger lahar volumes, even though the volume was not too huge. These conditions occurred on (1) 22 September 1888, when pyroclastic flow reached 7.5 km causing very large lahar in the Senowo, Trising, Blongkeng and Batang Rivers; (2) 18–19 December 1930, characterised with a pyroclastic flow which reached 13 km and caused large-scale lahar in all 13 major rivers from the southern slope to the west; (3) 8 May 1961 indicated with a pyroclastic flow which reached 12 km and caused large-scale lahar in the Senowo, Blongkeng, Batang, Bebeng and Pabelan Rivers, (4) 7–8 January 1969, characterised by a pyroclastic flow which reached 13.3 km and caused very large lahar in all 13 major rivers (Lavigne et al. 2000). The data show that the western side, especially the south-west, was the most affected area by lahar until the modern period. This process even continued until the eruption in 2010 when lahar flow which crossed the Krasak, Putih and Pabelan Rivers caused disruption to the traffic system connecting the provincial capitals of Yogyakarta Special Province and Central Java Province.

The more intensive deposition of lahar in the New Merapi period is related to the type of eruption that tends to be explosive with small-scale dome avalanches (Andreastuti et al. 2000, Newhall et al. 2000, Gertisser et al. 2012). The changes in the type of eruption have affected the development of landforms on the volcanic foot through the increasing deposition of lahar. This shows the contribution of volcanic activities in influencing the development of landforms in this region. Furthermore, Lavigne et al. (2000) say that there were 37 lahar cases in the Merapi volcanic foot between 1587 and 1998. The number of lahar events in 1 year varies. In years where a large lahar event occurs, it can reach 85 times. The south-west region experienced the most lahar events during this time span, especially in the Putih, Batang, Blongkeng and Krasak Rivers. This causes a relatively higher number of palaeochannels in the river valleys compared to other rivers in the study area (see Table 2).

The impact of the more frequent lahar events to the number of palaeochannel is supported by the explanation of Lavigne et al. (2000) and Lavigne and Thouret (2002) that lahar produces thick layers, especially in the deposition zones. This thick layer allows river channel displacement if lahar deposits cannot be overhauled by the flow that comes next. Meanwhile, the lahar flow is also a very strong erosion force. Bélizal et al. (2013) say that in the 2010 eruption, lahar flow caused morphological changes in river valleys due to the large capacity of erosion.

The lahar deposition process at the present time in all parts of the river valley is not the same as that of in the past. This is due to the large volume of sand mining on deposited lahar area, especially in the upstream of large rivers such as Gendol, Krasak (with main activities in Bebeng Area), Putih and Pabelan (in several branches of the river). The results of the field observations show that the lahar deposits resulted from the 2010 eruption fully loaded the dams that had been completely mined in 2019. This condition certainly affected the work process, as it did in the past.

Discussion

The results of this study indicate that there are many palaeochannels on the volcanic foot of Merapi Volcano. The existence of palaeochannels is inseparable from the volcanic activity of Merapi for a long time. Referring to the classification of surface palaeochannels described by Chen et al. (1996a, b), the palaeochannel observed in the study area is included in the category of trough-shaped palaeochannels. This type belongs to abandoned channels whose river beds are at the same level or lower than the surrounding plain. The rivers at the volcanic foot mostly carry lahar materials during the eruption period (Lavigne et al. 2000), whereas the lahar deposits are dismantled and transported as bed load in the inactive period. This is thought to be the cause of the relative form of palaeochannel. Meanwhile, the possibility of braided stream occurring in palaeorivers which carry a lot of bed load as explained by Bridge (1985), is also relatively small because of the strong volcanic activities, inhibiting the working of the fluvial process. It can be concluded that a joint volcanic and fluvial process occurs in the volcanic foot of the active volcano, and therefore it produces morphology with specific characteristics.

In this fluvio-volcanic system, the deposition of volcanic materials and the process of aggradation play an important role in the dynamics of river valley development. This study found the same condition when compared with the result of previous studies (Schumacher and Schmincke 1990, Palmer 1991, Wakabayashi 2013). The results of this study confirm the influence of active volcanism on the dynamics of palaeochannel development. Lahar deposition, as discovered by Palmer (1991), is a very influential process in damming river valleys in the volcanic foot of Merapi Volcano. Wakabayashi (2013) has shown that the palaeochannel evolution is very complex. It is influenced by a long-term deposition of sediment and erosion and a complex setting of the geological environment. Compared to this condition, the process that occurs at Merapi is much simpler and relies heavily on the volcanism due to the large amount of the deposited sediment. Instead of a strong and long-lasting erosion process, the river valley shifts are dominated by dams on the old river valley. The development of palaeochannel which is strongly influenced by volcanism is similar to that shown by Palmer (1991), where the palaeochannel which is >1 m deep is filled with lahar, while fluvial sediments are rarely found.

The fluvio-volcanic processes that affect the dynamics of river valleys have been investigated in previous studies. Paguican et al. (2009) conducted a study in the Mayon Volcano, Philippines, which found that the remobilisation of debris material into lahar flows had a major effect on both people's lives and the geomorphic processes in downstream areas. This study shows that at the fluvio-volcanic system, eruption materials can be overhauled by rainwater in the post-eruption years. If an eruption produces large amounts of materials and after the eruption is overhauled by heavy rain, it will form a large lahar flow which can break through the dike and settle outside the river valley in the downstream area. Grain size is also strongly correlated with erosion because fine-grained ash decreases the permeability and increases the runoff. The results of this study have answered our research problems, namely how deposition of lahar can dam river valleys, break through natural dikes, create new valleys and leave old valleys as palaeochannels. According to Lavigne et al. (2000), the depositional characteristics of lahar in the Merapi volcano are indeed coarse material, causing both aggradation and erosion. Many are triggered by heavy rains for several years after the eruption.

Harris et al. (2006) in their study at Santiaguito Volcano, Guatemala, obtained the same findings as that of Paguican et al. (2009) and this study. The research findings of Harris et al. (2006) show that eruption materials can cause aggradation for a year after eruption due to rainfall for 12 months. Lahar and river sedimentation are common problems in drainage basins blanketed by volcanic fallout, especially in areas of persistent fluvio-volcanic regime. Santiaguito has the same characteristics as Merapi, in that sustainable extrusion provides a persistent supply of sediment to the river system. The mobilisation of volcanic materials during the rainy season triggers lahar and aggradation during every rainy season. As a result, river channels are blocked, riverbeds become aggraded, tributaries are blocked and river channel shifting occurs.

The similar characters between Santiaguito and Merapi provides the probable information that palaeochannel formation in Merapi, as a result of river channel shifting, occurred persistently due to the high frequency of Merapi eruptions, especially in the past few centuries (Gertisser et al. 2012). In addition, Java Island, which is situated in the monsoon zone, always experiences the rainy season for about half a year. During November–April there is a lot of rain which triggers lahars (Lavigne et al. 2000). Palaeochannel in Merapi

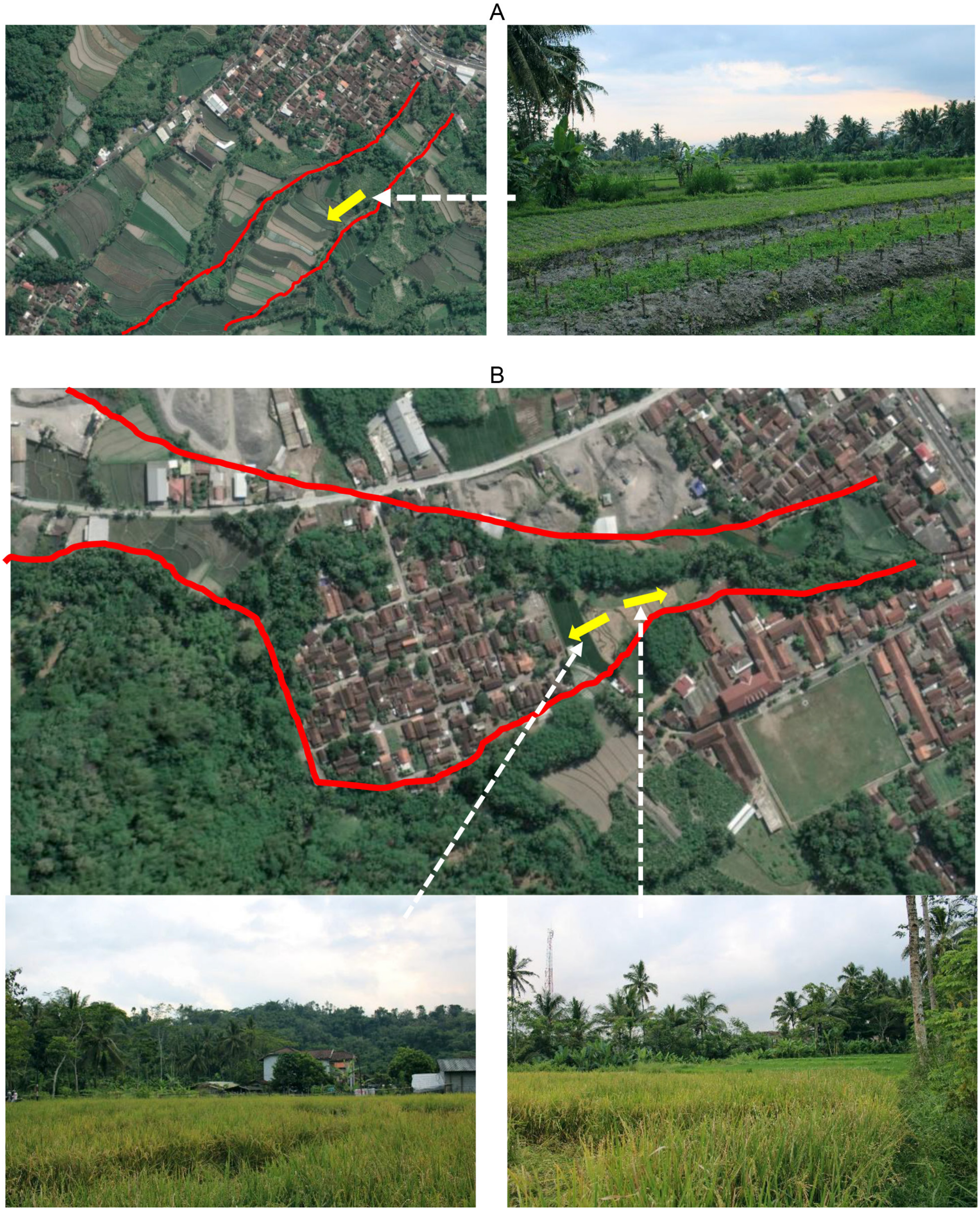


Fig. 7. The influences of topography on palaeochannel distribution in the south-west sector of Merapi volcanic foot. (A) palaeochannel which is deflected from NNE–SSW to ESE–WNW by Gendol Hill (bounded by red lines), located 230 m at the eastern of the Putih River, precisely at the north bank of Gendol Hill with altitude of 359 masl., (B) a non-deflected palaeochannel, NE–SW direction (bounded by red lines), located 400 m from the eastern edge of the Gendol Hills and 304 m at the western of the actual Batang River with altitude of 355 m a.s.l. Yellow arrows show the orientation of the field photograph. Source: Google Earth (2021).

is often found in the volcanic foot area, which is the medial zone. This condition is the same as the findings of Harris et al. (2006) in Santiaguito, where the channel location and over-banking of lahar material to emplace new deposits on the surrounding terrain constantly changes in the medial zone. After the VEI 4 eruption in 2010, the rain-triggered lava deposition process is still running. However, geomorphic processes such as damming, aggradation and channel shifting do not occur due to human activities in mining, normalisation of river flows and dike strengthening because of disaster mitigation.

Another study conducted by Harris et al. (2003) in the Santiaguito Volcano, showed that morphological factors and slope were very influential on the deposition of the eruption sediment. When the nature of eruption evolved from endogenous to exogenous dominance characterised by the Merapi-type nuee ardentes, many symptoms indicate that the depositional patterns of lava, pyroclastic and lahar material flow and deflect are based on the existing morphology. This study provides probable information on the palaeochannel pattern, which tends to follow the main valley pattern. The examination of the general slope of the digital elevation model (DEM) shows that the flat topography of the volcanic foot and the presence of the Gendol Hills on the south-west side of the palaeochannel tend to have more varied deflection in this part than in the south (Fig. 7). Information from the DEM shows that 97.82% of the study area has a slope of below 8%, especially in the southern sector. This is also shown by Lavigne et al. (2000) in mapping the distribution of lahar.

The pattern of palaeochannel distribution in the study area is affected by the volcanic process and morphology of stratovolcano. Compared with previous studies, it is clear that the fluvio-volcanic process is very decisive to the pattern of palaeochannel. The research conducted by Qinghai et al. (1996) in North China Plain, for example, shows that the distribution of palaeochannels in the region has a clustered pattern in the depression areas. The depression occurs due to the influence of tectonic processes which cause the river flow to cluster in the depression area, therefore palaeochannels also cluster in the depression area. In the Merapi volcanic foot, palaeochannel groupings occur in paths that are radially dispersed in the region due to the morphology of stratovolcano. Chen et al. (1996a, b), from the study also in North China Plain, explain that the distribution of palaeochannels also follows morphological units. A radial pattern of palaeochannels is found in the peidmont-alluvial fan zones, a parallel palaeochannel is found in the alluvial plain zone, and a branched palaeochannel is found in the coastal plain zone. The radial palaeochannel in the piedmont-alluvial fans correlates with the alluvial fan morphology patterns, which allow the formation of these radial patterns. The same conditions are found at the foot of the Merapi volcano, which is the lower part of the stratovolcano cone.

Conclusions

Volcanic activity has an important role in causing changes in landscape conditions rapidly in the surrounding environment. Palaeochannels that are found from the southern to western flanks of the Merapi volcanic foot are evidence that the volcanic process is a determining factor for changes in landscape conditions. The volcanic activity of Merapi through the deposition of lahar material causes the river channel shift to leave the dead river channel which is then found as a palaeochannel. This condition also shows that from the geomorphological features that we encounter today in the area around Merapi Volcano, apparently its formation is inseparable from the series of processes that have occurred continuously since the past. The development of palaeochannels which is influenced by volcanic processes also has specific characteristics when compared with processes that occur in other environments.

There are several things that need to be done in further research, including the dynamics of the palaeochannel which is far from the present river valley, as well as the buried palaeochannel that might exist in this region. Future research is highly recommended to explore buried palaeochannels in relation to past Merapi activities. Studies that have been carried out to uncover the palaeochannel along with the background of genesis and the processes that influence it from the past can provide a comprehensive image that is important for resource use efforts and for recognition of the potential hazards in this region.

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Author's contribution

AA conceived the presented idea and performed the field measurements and analysis with support from EW. AA wrote the manuscript with support from SP. SP supervised the project. NA performed remote sensing analysis. EW performed GIS analysis and designed the maps. All the authors discussed the results and contributed to the final manuscript.

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